Angular structure of diffraction dissociation at LHC

S. M. Troshin, N. E. Tyurin

Institute for High Energy Physics,

142280 Protvino, Moscow Region, Russia

Abstract

We consider angular dependence of the diffractive dissociation processes at high energies. It appeared that angular dependence of the diffractive dissociation has no dip and bump structure at the LHC energies and would show a smooth power-like decrease with t. The normalized differential cross-section has a scaling behavior and depends on the ratio $-t/M^2$ only. These results reflect general trends of unitarity limitations at high energies and are realized within the chiral quark model with unitarization performed through the generalized reaction matrix.

Introduction

During recent years CERN, DESY and FNAL have been producing interesting results on diffractive production in hadron and deep-inelastic processes [1]. Discovery of hard diffraction at CERN S$\bar{p}p$S and diffractive events in the deep-inelastic scattering at HERA were among the most surprising results obtained recently. Significant fraction of high-t events among the diffractive events in deep-inelastic scattering and hadron-hadron interactions were also observed at HERA and Tevatron respectively. These experimental discoveries renewed interest in the experimental and theoretical studies of the diffractive production processes.

The understanding of the diffractive interactions plays fundamental role in the studies of a high-energy limit of the modern strong interaction theory — QCD. This field is most interesting one since there are no firmly established computational methods within QCD. However, the progress in understanding of high–energy basic features and the underlying dynamics of diffraction mechanism can be traced in the recent theoretical papers (cf. review [2]).

It is of high importance to have the experimental data at highest possible energy and there is no doubt that soft and hard diffractive processes should be measured at the LHC. Besides elastic scattering (total and elastic cross-sections) it is important to measure the inelastic diffractive final states, jet production, hadron transverse momentum distribution, strange and charmed particle productions. The single diffraction dissociation is a most simple inelastic diffractive process and studies of soft and hard final states in this process could become a next step after elastic measurements. Such measurements are crucial for understanding of the microscopic nature of driving mechanism called Pomeron, its possible parton structure, high-energy limit of strong interactions and approaching the asymptotia.

At the currently available energies there were obtained several sets of the experimental data for single diffraction production process

$$h_1 + h_2 \to h_1 + h_2^* \tag{1}$$

when the hadron h_2 is excited to the state h_2^* with invariant mass M and the same quantum numbers. Its subsequent decay results in the multiparticle final state. The inclusive differential cross–section shows a simple dependence on the invariant mass M:

$$\frac{d\sigma_{diff}}{dM^2} \propto \frac{1}{M^2}. \tag{2}$$

Meanwhile, energy dependence of the diffractive production cross–section $\sigma_{diff}(s)$ is not so evident from the experimental data. The data obtained at FNAL seem to demonstrate a growing diffractive cross–section but some data obtained at CERN may indicate a falling diffractive cross–section. Resolution of this problem is important in particular for the study of the role of unitarity in the inelastic diffraction and its asymptotical properties.

The angular dependence of the diffractive dissociation is even less clear. Similarity between elastic and inelastic diffraction in the t-channel approach suggests that the latter one would have similar to elastic scattering behavior of the differential cross-section. However, it cannot be taken for granted and e.g. transverse momentum distribution of diffractive events in the deep-inelastic scattering at HERA shows a power-like behavior with no apparent dips [3]. Similar behavior was observed also in the hadronic diffraction dissociation process at CERN [4] where also no dip and bump structure was observed. Angular dependence of diffraction dissociation together with the measurements of the differential cross–section in elastic scattering would allow to determine the geometrical properties of elastic and inelastic diffraction, their similar and distinctive features and origin.

The experimental regularities of diffractive production can be described in the framework of different approaches, e.g. models for inelastic diffraction based on

s-channel absorptive unitarity were considered in [5], optical approach was used in [6], dipole Pomeron and effective Pomeron with energy-dependent intercept were applied in Refs. [7] and [8], respectively. $1/M^2$ dependence is naturally described by the triple–pomeron diagrams in the framework of Regge–model [9]. The proposed in Ref. [10] similarity between the pomeron and photon exchanges allowed to calculate diffractive dissociation cross–section in terms of structure function νW_2 measured in deep inelastic lepton scattering. The explanation of M^2–dependence in the framework of optical model considering diffractive dissociation as a bremsstrahlung where virtual quanta are released from a strong field was made in Ref. [11]. Explanation of the smallness of a large mass diffraction as a result of the strong non-perturbative interaction of gluons was given in [12]. The list of the above references is certainly far from being complete and many theoretical papers devoted to the various aspects of diffractive production were not mentioned.

In Ref. [13] for the description of single diffractive processes we used geometrical notions on quark scattering in approach based on unitarity for the scattering amplitude and chiral quark model for hadron structure. Motivated by the importance of this process for the study of long distance dynamics we have shown how the energy and M^2–dependencies can be obtained in the approach to hadron interactions with account for the spontaneous breaking of chiral symmetry and presence of a quark condensate inside a hadron.

In this paper we consider transverse momentum distribution in the framework of the above approach and show that the diffraction cone would be suppressed and disappears at LHC energy in the production process $p+p\to p+X$.

1 Amplitude of the diffractive production

To construct the amplitude of the diffractive production process let us remind that the unitary equation for the scattering amplitude

$$\mathrm{Im} f(s,b) = |f(s,b)|^2 + \eta(s,b) \tag{3}$$

allows one to express the inelastic channel contribution

$$\eta(s,b) = \sum_n \sigma_n(s,b) \tag{4}$$

through the U-matrix

$$\eta(s,b) = \mathrm{Im} U(s,b)|1 - iU(s,b)|^{-2}, \tag{5}$$

and to get respectively the total inelastic cross-section

$$\sigma_{inel}(s) = 8\pi \int_0^\infty bdb \frac{\mathrm{Im}U(s,b)}{|1-iU(s,b)|^2}. \tag{6}$$

The quantity $\mathrm{Im}U(s,b)$ can be represented in the following form

$$\mathrm{Im}U(s,b) = \sum_n \bar{U}_n(s,b), \tag{7}$$

where

$$\bar{U}_n(s,b) = \int d\Gamma_n |U_n(s,b,\{\xi_n\}) \tag{8}$$

and $d\Gamma_n$ is an element of n-particle phase space volume and $\{\xi_n\}$ is the set of kinematical variables related to the n–particle final state. Sum in the right hand side of this equation runs over all inelastic final states which include as well diffractive as non-diffractive ones. To obtain the cross-section of the diffractive dissociation process (1) we should single out in this sum the final states corresponding to the process (1) . Let for simplicity consider the case of pure imaginary U-matrix, i.e. $U \to iU$. Then we can represent $d\sigma_{diff}/dM^2$ in the form

$$\frac{d\sigma_{diff}}{dM^2} = 8\pi \int_0^\infty bdb \frac{U_{diff}(s,b,M)}{[1+U(s,b)]^2} \tag{9}$$

where $U_{diff}(s,b,M)$ includes contributions from all the final states $|n\rangle_{diff}$ which result from the decay of the excited hadron h_2^* of mass M: $h_2^* \to |n\rangle_{diff}$. The corresponding impact parameter amplitude $F_{diff}(s,b,M)$ can be written in this pure imaginary case as a square root of the cross-section, i.e.

$$F_{diff}(s,b,M) = \sqrt{U_{diff}(s,b,M)}/[1+U(s,b)] \tag{10}$$

and the amplitude $F_{diff}(s,t,M)$ is

$$F_{diff}(s,t,M) = \frac{is}{\pi^2} \int_0^\infty bdb J_0(b\sqrt{-t}) \sqrt{U_{diff}(s,b,M)}/[1+U(s,b)]. \tag{11}$$

In Refs. [13, 14] we used the notions of effective chiral quark model for the description of elastic scattering and diffractive production. Different aspects of hadron dynamics were accounted in the framework of effective Lagrangian approach. The picture used for the hadron structure implies that overlapping and interaction of peripheral condensates at hadron collision occurs at the first stage. In the overlapping region the condensates interact and as a result the massive quarks

appear. Those quarks are transient ones: they are transformed back into the condensates of the final hadrons in elastic scattering and the diffraction dissociation processes. In elastic scattering each of the constituent valence quarks located in the central part of the hadron is supposed in the model to scatter in a quasi-independent way by the produced virtual quark pairs at given impact parameter and by the other valence quarks.

For consideration of the diffractive production at the quark level we have extended the picture of hadron interaction in case of elastic scattering [14]. Since the constituent quark is an extended object there is a non–zero probability of its excitation at the first stage of hadron interaction when peripheral condensates interact. Therefore it seems rather natural to assume that the origin of diffractive production process is an excitation of one of the valence quarks in colliding hadron: $Q \to Q^*$, its subsequent scattering and then decay into the final state. The excited constituent quark is scattered similar to other valence quarks in a quasi-independent way. The function $U_{diff}(s,b,M)$ can be represented then as a product

$$U_{diff}(s,b,M) = \prod_{Q=1}^{N-1} \langle f_Q(s,b) \rangle \langle f_{Q^*}(s,b,M_{Q^*}) \rangle, \tag{12}$$

where M_{Q^*} is the mass of excited constituent quark. This mass is taken to be proportional to the mass M of excited hadron h_2^*. This assumption is based on the additivity of constituent quark masses in the hadron and the absence of the diffractive radiation from the other constituent quarks.

In the model the b–dependence of the amplitudes $\langle f_Q \rangle$ and $\langle f_{Q^*} \rangle$ is related to formfactor of the constituent quark and excited constituent quark respectively. The strong interaction radius of constituent quark is determined by its mass. We suppose that the same is valid for the size of excited quark, i.e. $r_{Q^*} = \xi / M_{Q^*}$. The expression for $U_{diff}(s,b,M)$ can be rewritten then in the following form:

$$U_{diff}(s,b,M) = g^* U(s,b) \exp[-(M_{Q*} - m_Q) b/\xi], \tag{13}$$

where constant g^* is proportional to the relative probability of excitation of the constituent quark. The value of g^* is a non-zero one, however, $g^* < 1$ since we expect that the excitation of any constituent quark has lower probability compared to the probability for this quark to stay unexcited. The excited quark is unstable and its subsequent decay is associated with the decay of hadron h_2^* into the multiparticle final state $|n\rangle_{diff}$. The expression for $U(s,b)$ is the following [13]:

$$U(s,b) = g(s) \exp(-\tilde{M} b/\xi) \equiv \tilde{G} \left[1 + \alpha \frac{\sqrt{s}}{m_Q} \right]^N \exp(-\tilde{M} b/\xi), \tag{14}$$

where $\tilde{M} = \sum_{Q=1}^{N} m_Q$ and N is the total number of the constituent quarks in colliding hadrons.

2 Total and differential cross-sections of the diffractive production

The cross-section of diffractive dissociation process is given by Eq. (9) and has the following s and M^2 dependence

$$\frac{d\sigma_{diff}}{dM^2} \simeq \frac{8\pi g^* \xi^2}{(M_{Q^*} - m_Q^2)^2}\eta(s,0) \simeq \frac{8\pi g^* \xi^2}{M^2}\eta(s,0) \qquad (15)$$

Thus, we have a familiar $1/M^2$ dependence of the diffraction cross-section which is related in our model to the geometrical size of excited constituent quark. The energy dependence of single diffractive cross-section has the form

$$\sigma_{diff}(s) = 8\pi g^* \xi^2 \eta(s,0) \int_{M_0^2}^{M_1^2} \frac{dM^2}{M^2} = 8\pi g^* \xi^2 \eta(s,0) \ln \frac{s(1-x_1)}{M_0^2}, \qquad (16)$$

where x_1 is the lower limit of the relative momentum of hadron h_1 and corresponds to the experimental constraint on diffractive process $x_1 \simeq 0.8 - 0.9$. Eq. (16) shows that the total cross-section of diffractive dissociation has a non-trivial energy dependence which is determined by the contribution of inelastic channels into unitarity equation at zero value of impact parameter. The dependence of $\eta(s,0)$ is determined by Eq. (5), where $U(s,b)$ is given by Eq. (14).

At $s \leq s_0$, (s_0 is determined by equation $|U(s_0,0)| = 1$) $\eta(s,0)$ increases with energy. This increase as it follows from Eq. (14) and from the experimental data [15] is rather slow one. However at $s \geq s_0$, $\eta(s,0)$ reaches its maximum value $\eta(s,0) = 1/4$ and at $s > s_0$, the function $\eta(s,0)$ decreases with energy and at asymptotical energies the inelastic diffraction cross section drops to zero. But at the LHC energy $\sqrt{s} = 14\ GeV$ the single diffractive inelastic cross-sections can reach the value of 2.4 mb [16] and therefore might be quite significant.

Hence, it worth to consider the structure of the corresponding angular distribution. The corresponding amplitude $F_{diff}(s,t,M)$ can be calculated analytically. To do so we continue the amplitudes $F_{diff}(s,\beta,M)$, $\beta = b^2$, to the complex β–plane and transform the Fourier–Bessel integral over impact parameter into the integral in the complex β – plane over the contour C which goes around the positive semiaxis. Then for the amplitude $F_{diff}(s,t,M)$ the following representation takes place:

$$F_{diff}(s,t,M) = -\frac{is}{2\pi^3}\int_C d\beta F_{diff}(s,\beta,M) K_0(\sqrt{t\beta}) \qquad (17)$$

where $K_0(x)$ is the modified Bessel function. The amplitude $F_{diff}(s,\beta,M)$ has the poles in the β–plane determined by equation

$$1 + U(s,\beta) = 0. \qquad (18)$$

The solutions of this equation can be written as

$$\beta_n(s) = \frac{\xi^2}{\tilde{M}^2}\,\{\ln g(s) + \,i\pi n\}\,,\; n = \pm 1, \pm 3, \ldots \qquad (19)$$

The amplitude $F_{diff}(s, \beta, M)$ besides the poles has a branching point at $\beta = 0$.

Therefore the amplitude $F_{diff}(s, t, M)$ can be represented as a sum of the pole contribution and the contribution of the cut:

$$F_{diff}(s, t, M) = F_{diff,p}(s, t, M) + F_{diff,c}(s, t, M) \qquad (20)$$

Up to this point the calculation is similar to the case of elastic scattering. For elastic scattering amplitude $F(s, t)$ the pole and cut contributions are decoupled dynamically when $g(s) \to \infty$ at $s \to \infty$ [17]. Contribution of the poles determines the elastic amplitude in the region $|t|/s \ll 1$ $(t \neq 0)$. The amplitude in this region can be represented in a form of series over the parameter $\tau(\sqrt{-t})$:

$$F(s, t) = s \sum_{k=1}^{\infty} \tau^k(\sqrt{-t})\varphi_k[R(s), \sqrt{-t}], \qquad (21)$$

where $\varphi_k[R(s), \sqrt{-t}]$ are the oscillating functions of the variable $\sqrt{-t}$. The parameter τ decreases exponentially with $\sqrt{-t}$:

$$\tau(\sqrt{-t}) = \exp(-\frac{2\pi\xi}{\tilde{M}}\sqrt{-t}).$$

This series reproduces diffraction peak and familiar dip-bump structure of the differential cross-section in elastic scattering. In the region of moderate t it is sufficient to take into account few or even one of the terms of series Eq. 21. The differential cross-section in this region has familiar Orear behavior.

However, the situation is different in the case of diffraction production. Instead of dynamical separation of the pole and cut contribution discussed above when

$$F_p = O(s \ln^{1/2} g(s)), \quad F_c = O(s[g(s)]^{-1}), \qquad (22)$$

we have a suppression of the pole contribution at high energies since at fixed t

$$F_{diff,p} = O(s[g(s)]^{-\frac{M}{2\tilde{M}}} \ln^{1/2} g(s)), \quad F_{diff,c} = O(s[g(s)]^{-\frac{1}{2}}), \qquad (23)$$

i.e. the pole contribution is suppressed at high energies where $g(s) > 1$ since $M > \tilde{M}$. Therefore, at all t values we will have

$$F_{diff}(s, t, M) \simeq F_{diff,c}(s, t, M), \qquad (24)$$

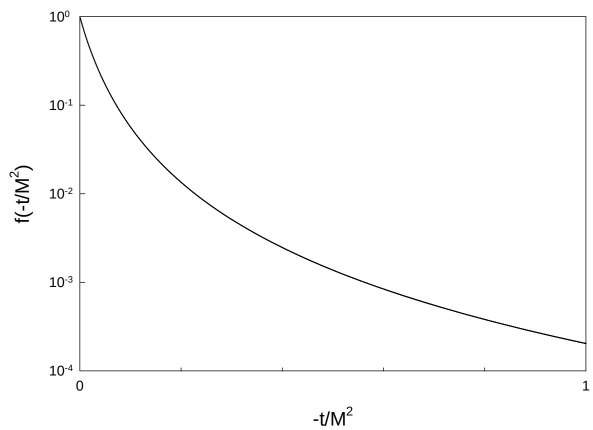

Figure 1: Scaling behavior of the normalized differential cross-section $\frac{1}{\sigma_0}\frac{d\sigma}{dtdM^2}$.

where

$$F_{diff,c}(s,t,M) \simeq ig^* g^{-1/2}(s)(1-\frac{t}{\bar{M}^2})^{-3/2}, \tag{25}$$

where $\bar{M} = (M - \tilde{M} - 1)/2\xi$. This means that the differential cross-section of the diffraction production will have smooth dependence on t with no apparent dips and bumps

$$\frac{d\sigma_{diff}}{dtdM^2} \propto (1-\frac{t}{\bar{M}^2})^{-3}. \tag{26}$$

It is interesting to note that at large values of $M \gg \tilde{M}$ the normalized differential cross-section $\frac{1}{\sigma_0}\frac{d\sigma}{dtdM^2}$ (σ_0 is the value of cross-section at $t=0$) will exhibit scaling behavior

$$\frac{1}{\sigma_0}\frac{d\sigma}{dtdM^2} = f(-t/M^2), \tag{27}$$

and explicit form of the function $f(-t/M^2)$ is the following

$$f(-t/M^2) = (1-4\xi^2 t/M^2)^{-3}. \tag{28}$$

The numerical parameter ξ in the model is about 2. The function Eq. (27) against the variable $-t/M^2$ is depicted in the Fig. 1.

The above scaling has been obtained in the model approach, however it might have a more general meaning.

The angular structure of diffraction dissociation processes given by Eq. (26) takes place at high energies where $g(s) > 1$ while at moderate energies where $g(s) \simeq 1$ the both contributions from poles and cut are significant. At low energies where $g(s) \ll 1$ the situation is similar to the elastic scattering, i.e. there diffraction cone and possible dip-bump structure should be present in the region of small values of t. In this region

$$F_{diff}(s,t,M^2) = s\sum_{k=1}^{\infty}\tau^k(\sqrt{-t})\varphi_{diff,k}[R(s),\sqrt{-t},M^2], \tag{29}$$

where the parameter $\tau(\sqrt{-t})$ is the same as in the elastic case and

$$\varphi_{diff,k} = O(s[g(s)]^{-\frac{M}{2\tilde{M}}}\ln^{1/2} g(s)). \tag{30}$$

Conclusion

We considered behavior of the differential cross-section for single inelastic diffraction. At low and moderate energies behavior of the differential cross-section will be rather complicated and incorporate diffraction cone, Orear type and power-like dependencies.

However, at high energies a simple power-like dependence on t is predicted. It was shown that the normalized differential cross-section has a scaling form and only depends on the ratio $-t/M^2$ at large values of M^2.

In fact, our particular comparative analysis of the poles and cut contributions has very little with the model form of the U–matrix. The approach is based on the combination of unitarity with the diffraction production mechanism via excitation and subsequent decay of a constituent quark. This is why it may have a more general meaning.

At the LHC energy the diffractive events with the masses as large as 3 TeV could be studied. It would be interesting to check this prediction at the LHC where the scaling and simple power-like behavior of diffraction dissociation differential cross-section should be observed. Observation of such behavior would confirm the diffraction mechanism based on excitation of the complex hadron-like colorless object - constituent quark. This mechanism can in principle explain angular structure of diffraction in the deep - inelastic scattering at HERA where smooth angular dependence on the thrust transverse momentum was observed [3]. If it is the case, then diffraction in DIS at lower energies should manifest typical soft diffractive behavior with exponential peak at small t as it does in hadronic

reactions. It would be interesting to check it at lower energies, e. g. at Jefferson Lab.

There could be envisaged various experimental configurations at the LHC; e.g. soft diffraction goes well to the interest of the TOTEM experiment, while hard diffractive final states can be measured by CMS detector and possible correlations between the features of the soft and hard diffractive processes can be obtained using combined measurements of TOTEM and CMS [18].

Measurements of the angular dependence of diffraction dissociation simultaneously with the measurements of the differential cross–section of elastic scattering are important for the determination of the global geometrical properties of elastic and inelastic diffraction, their similar and distinctive features and the origin and nature of the driving asymptotic mechanism. In general these studies could be an essential tool to probe non-perturbative QCD.

Acknowledgements

We are grateful to V. A. Petrov for the interesting discussions and comments. This work was supported by RFBR (Grant No. 99-02-17995).

References

[1] D. M. Jansen, M. Albrow and R. Brugnera, Proceedings of 7th International Workshop on Deep Inelastic Scattering and QCD (DIS 99), Zeuthen, Germany, 19-23 April 1999, Nucl. Phys. Proc. Suppl. 79 (1999) 732.

[2] A. Hebecker and T. Teubner, hep-ph/0006234.

[3] C. Adloff et al., Eur. Phys. J. C10 (1998) 443.

[4] A. Brandt et al., Nucl. Phys. B 514 (1998) 3.

[5] L. Caneschi and G. Delfino, Phys. Lett. B 253 (1991) 261.

[6] T. Meng, R. Rittel, K. Tabelow and Z. Yang, hep-ph/9910331.

[7] L. L. Jenkovszky, E. S. Martynov and F. Paccanoni, hep-ph/9608386.

[8] S. Erhan and P. Schlein, Phys. Lett. B 481 (2000) 177.

[9] A. Mueller, Phys. Rev. D2 (1970) 2963; D4 (1971) 150;
A. B. Kaidalov, Phys. Rept. 50 (1979) 157.

[10] A. Donnachie and P.V. Landshoff, Phys. Lett B185 (1987) 403 ; Nucl. Phys. B311 (1988) 509.

[11] K.H. Dederichs and M. A. Fassler, Phys. Lett. B232 (1989) 405.

[12] B. Z. Kopeliovich, A. Schäfer and A. V. Tarasov, Phys. Rev. D62 (2000) 054022.

[13] S. M. Troshin and N. E. Tyurin, Z. Phys. C 64 (1994) 311.

[14] S.M. Troshin and N.E. Tyurin, Nuovo Cim. A106 (1993) 327.

[15] H.I. Miettinen and J. Pumplin, Phys. Rev. D18 (1978) 1696.

[16] S. M. Troshin and N. E. Tyurin, hep-ph/0004084.

[17] S.M. Troshin and N.E. Tyurin, Phys. Rev. D49 (1994) 4427.

[18] V. A. Petrov, talk given at the International Symposium " LHC Physics and Detectors", Dubna, 28-30 June 2000.